Design of a Low-Cost, In-Situ, Non-Contact, Temperature Sensor for Variable-Emissivity Surfaces in CIGS Deposition

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ABSTRACT

A low-cost, non-contact sensor was designed that simultaneously measures substrate temperature and emissivity. The sensor measures these quantities based on the changes in both magnitude and wavelength distribution of thermal radiation that occur with changes in temperature. Preliminary ex-situ measurements have confirmed the validity of the design. A number of aspects of the sensor verification, however, remain as future work.

1. Background

Substrate temperature is critical for CIGS depositions. Typical laboratory deposition systems monitor substrate temperature carefully through the use of thermocouples on the back of the substrate. Such a configuration is problematic for production systems, where substrates are constantly moving through the system. Although heater temperatures are commonly monitored, changes in deposition conditions may change the relationship between heater temperatures and the actual substrate temperatures. For flexible substrates, thermocouple temperature measurement is particularly problematic, since the low thermal mass of the substrate implies that contact with thermocouples actually changes the substrate temperature.

Based on typical CIGS operating conditions, it was determined that the sensor must have the following characteristics: (1) Range of 200 to 700 ^{o}C, with ±10 ^{o}C accuracy, (2) Ability to measure materials with unknown emissivities in the range of 0.05 to 1, (3) Ability to survive 600 ^{o}C Se-containing ambient, and (4) Low cost.

Off-the-shelf infrared (IR) systems do not satisfy the above criteria. Many require emissivities to be both known and high. Certain commercially-available “two-color” sensors allow temperature measurement independent of emissivity. However, such systems typically provide valid data no lower in temperature than 450 ^{o}C, and they require use of bifurcated fiber optics that cannot withstand the necessary temperatures.

2. Principles of Operation

A low-cost, non-contact sensor was designed that simultaneously measures substrate temperature and emissivity. The sensor measures these quantities based both magnitude and wavelength distribution of thermal radiation. Figure 1 shows the power density radiated, as a function of wavelength, at two different temperatures and emissivities. Also shown are the wavelength response regions for two different IR sensors. Calculations are according to Plank’s law [1]. At a fixed temperature, the magnitude of the radiation is proportional to the emissivity. At a fixed emissivity, the magnitude of the thermal radiation increases and shifts to shorter wavelengths with increasing temperature. Thus, the ratio of the signals from the long- and short-wavelength sensors will indicate the temperature, regardless of the emissivity. The emissivity can then be calculated using the deduced temperature and the magnitude of the overall radiation.

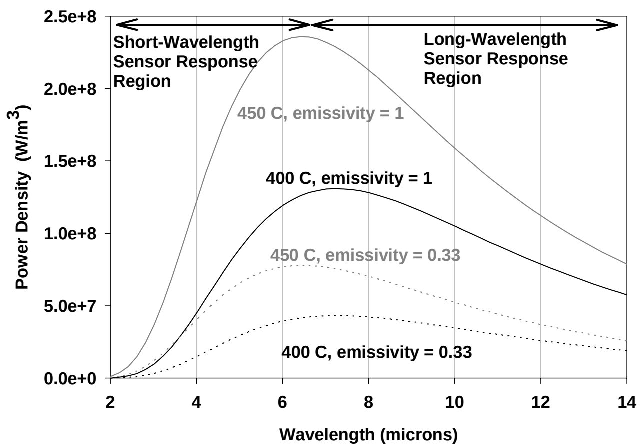

Figure 1: Magnitude and distribution of thermal radiation for two different emissivity bodies at two different temperatures. The wavelength response regions of two IR sensors are also shown.

Two sensors were purchased to cover the wavelength regions illustrated in Figure 1. The sensors are commercially-available thermopiles costing around $400. The responsivity of each sensor was defined as a function of wavelength and power. This calibration was achieved using a blackbody cavity furnace of adjustable temperature and various apertures. The furnace temperature was varied to change the incident spectral distribution, and the amount of radiation for a given distribution was varied using pie-shaped apertures.

3. Ex-Situ Results

Preliminary measurements were performed ex-situ on a hot plate, using samples with a variety of emissivities.

Meaningful data analysis requires allowing for wavelength-dependent emissivity. The IR sensors were calibrated using a blackbody furnace with an emissivity of 1 over the entire spectral range of both sensors. If the test sample emissivity is wavelength-dependent over from 3.5 to 20 μm, the signal ratio between the two sensors changes from the calbration. The necessity of allowing for wavelength-dependent emissivity was evidenced in gray-body analysis by temperature offsets between thermocoouple and IR results, and by apparent temperature-dependence of emissivity.

Published data [2,3] shows that the wavelength-dependence of the emissivity of metals in the range of interest can be empirically described the form

$$\varepsilon = m \ln(\lambda) + b \quad (1)$$

where ε = emissivity, λ = wavelength, and m and b are parameters of the fit. The value of m was adjusted for each material to minimize the temperature-dependence of the emissivity. Thermocouple and non-contact temperature measurements show reasonable agreement. Figure 2 compares temperature for each material as measured by thermocouple and IR thermometry. For the metals, the results agree within a few degrees at all temperatures. For glass, the disagreement is larger. The wavelength-dependence of glass emissivity may be more dramatic than the form assumed for the metals [4]. Figure 3 shows measured emissivity as a function of hot plate setting for each material. The Cu sample visibly oxidized during the measurement, as reflected in the increasing emissivity with time. Values are in agreement with the literature [5], although wide ranges are quoted for metal surfaces with varying degrees of oxidation.

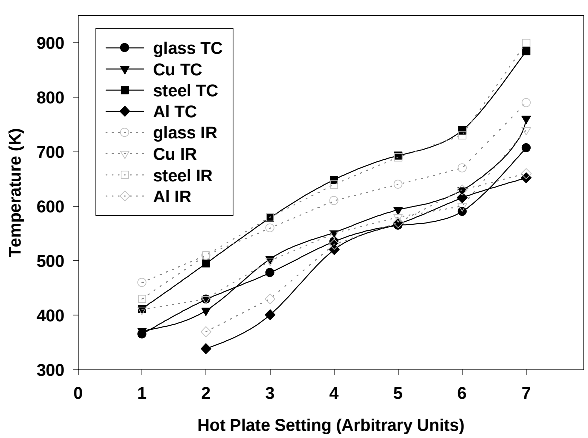

Figure 2 : temperature as a function of hot plate setting, assuming variation emissivity with wavelength

4. In-Situ Design

In-situ implementation of the IR thermometer requires several precautions. The sensor must be protected from Se, cooled adequately, maintained at a known temperature so that output can be corrected, and screened from reflection from hot evaporation sources.

A satisfactory enclosure was designed. The sensors measure through a ZnSe window which is heated to drive off Se. The sensors are surrounded by water cooling coils inside the enclosure. Thermocouples monitor the temperatures of the ZnSe window and the sensors, as necessary for accurate data analysis. Signal wires exit the enclosure through a cooled path, which prevents Se vapor from entering the enclosure. The enclosure design is similar to that which was used successfully to implement x-ray fluorescence in-situ. A shield surrounds the measurement area. The shield is outside the field of view of the sensors, but it prevents radiation from the nearby heat sources from hitting the measurement area and being reflected into the sensors.

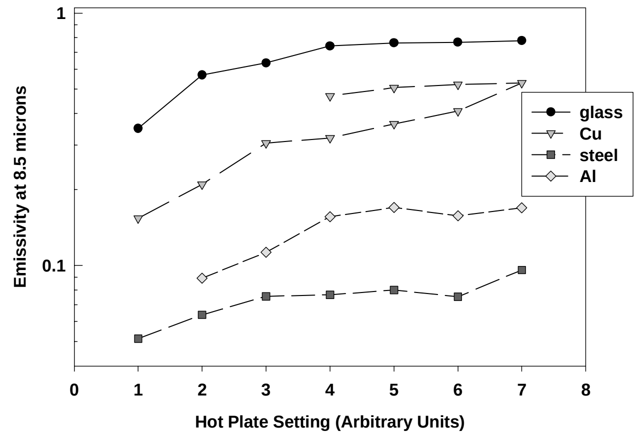

Figure 3: Measured emissivity at 8.5 microns wavelength, as a function of hot plate setting, assuming variation emissivity with wavelength.

5. Future Work

A number of aspects of the sensor development remain as future work. First, the necessity to account for wavelength-dependent emissivity has implications for the temperature measurement. Calibration of IR sensors with a blackbody furnace may not be sufficient for all samples. The wavelength behavior of CIGS emissivity must be investigated. Second, full in-situ testing of the sensor must be performed. Such testing involves verifying that 1) the proposed design adequately protects the sensor from Se, 2) the emission from the ZnSe window can be removed from the signal, 3) the sensor is adequately cooled, and 4) reflections from heaters and sources are adequately screened from the sensor.

ACKNOWLEDGEMENTS

Sensor development was funded by the NREL through Thin Film Partnership subcontract ZAK-8-17619-08. Current in-situ implementation performed under AFRL SBIR contract #F29601-00-C-0030.

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